(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

CORRECTED VERSION

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
10 January 2002 (10.01.2002)

PCT

(10) International Publication Number
WO 02/003567 A3

(51) International Patent Classification[7]: H04B 7/005

(21) International Application Number: PCT/US01/41061

(22) International Filing Date: 20 June 2001 (20.06.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/598,341 21 June 2000 (21.06.2000) US

(71) Applicant: CORNELL RESEARCH FOUNDATION, INC. [US/US]; Suite 105, 20 Thornwood Drive, Ithaca, NY 14850 (US).

(72) Inventors: HAAS, Zygmunt, J.; P.O. Box 176, Millburn, NJ 07041 (US). SANCHEZ, Miguel; Camino de Vera s/n, E-46020 Valencia (ES).

(74) Agents: CAHILL, Ronald, E. et al.; Nutter, McClennen & Fish, LLP, One International Place, Boston, MA 02110-2699 (US).

(81) Designated States *(national)*: CA, JP.

(84) Designated States *(regional)*: European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR).

Declaration under Rule 4.17:
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations CA, JP, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR)*

Published:
— *with international search report*

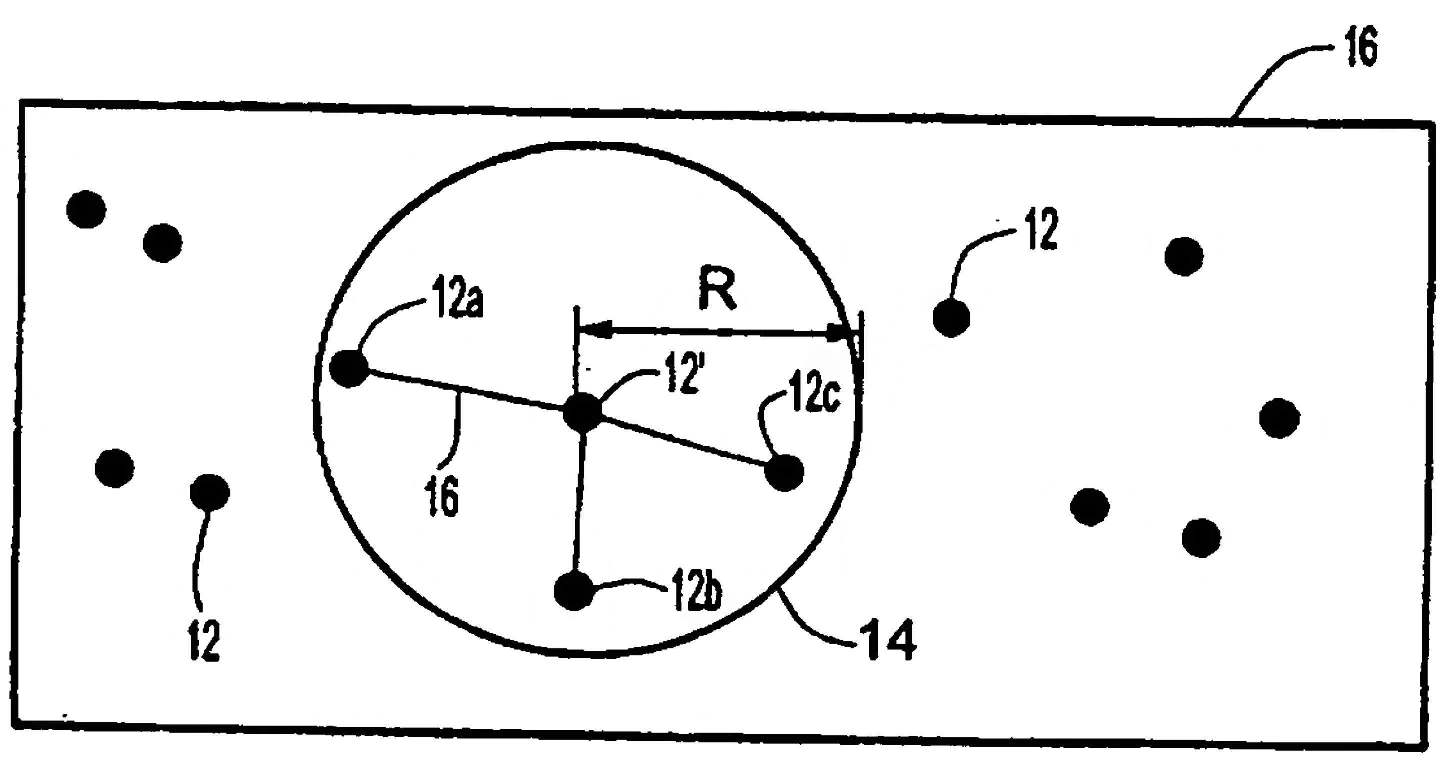
(88) Date of publication of the international search report: 18 July 2002

(48) Date of publication of this corrected version: 10 October 2002

(15) Information about Correction:
see PCT Gazette No. 41/2002 of 10 October 2002, Section II

[Continued on next page]

(54) Title: ADAPTIVE POWER CONTROL FOR WIRELESS NETWORKS



(57) Abstract: Power control techniques in wireless network for reducing mobile nodes' power consumption and achieving lower signal-to-interference ratio are disclosed. The proposed power control scheme for distributed networks discloses a method for adapting and storing the power level for transmission between the nodes. For each node that communicates with other nodes in the network the power level is calculated and stored in the node's memory (power cache). Each node continuously builds up its power cache. The calculation of the required transmission power level is done either at the receiving node or at the transmitting node. The resulting calculated power level is stored at the transmitting node for reference and for use in future transmissions.

WO 02/003567 A3

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

ADAPTIVE POWER CONTROL FOR WIRELESS NETWORKS

FIELD OF THE INVENTION

The present invention relates generally to the field of wireless communication networks and to the task of increasing the total network throughput by decreasing transmission power used by the network nodes. In particular, the invention relates to an ad hoc wireless network in which each transmitting node uses an adjusted power level to transmit data to a receiving node. However, the techniques presented here can also be applied to other types of wireless networks, which are not necessarily ad hoc networks. The values of the power levels are calculated by the nodes and stored in a cache maintained by each node.

BACKGROUND OF THE INVENTION

Cellular systems and most other wireless networks consist of a set of mobile nodes and an infrastructure that contains fixed base stations. In contrast, mobile *ad hoc* networks are networks that lack any fixed infrastructure. In particular, there are no central elements, such as base stations. The network nodes are all the elements of the network. In such networks, inter-nodal communication can be either direct, when the distance between communicating nodes is relatively small, or by means of other intermediate nodes that perform the routing and the forwarding functions. Therefore, each node has a double mission in-the network: it acts as a communication end point and as a router for other nodes' traffic. Because some of the network nodes are portable (mobile), important issues of network operation become, first, the weight of a portable communication device and, second, the ability of the nodes to operate for long periods of time before recharging. The second issue is usually referred to as *autonomy*. Since the main power source of portable nodes is their batteries, to ensure reasonable nodal autonomy, the batteries usually constitute a significant portion of the total mobile device's weight and volume. Therefore, techniques that reduce the battery power drainage continue to be of significant importance.

Furthermore, since transmission of data is one of the most power-intensive functions of a mobile node, transmission power control algorithms have been developed to reduce the power consumption of the nodes as much as possible, while maintaining full network connectivity. The added benefit of the power reducing approach is that it

also possibly may lead to the increase in the signal-to-interference ratio (SIR), improving the network capacity and the ability to provide connectivity to a higher density of nodes in the same area. Such an approach has been developed and used in cellular and satellite communication systems.

Because of the centralized nature of most of the satellite and cellular systems, the known techniques for power control cannot be easily applied to and implemented in distributed networks. The main reason for that difficulty is that in the cellular and satellite networks the central elements can perform much of the power controlling functionality. Since mobile ad-hoc networks are completely distributed and lack central control, there is a need to develop new power control techniques performing power control functions in the mobile ad-hoc communication environment.

It is also desirable to lower the transmission power in order to reduce the coverage area of the transmission and, consequently, to improve the spatial reuse of other transmissions between the nodes in the network. In other words, there is a benefit in providing power control methods that reduce the nodal transmission area by reducing the nodal transmission power, so that more transmissions can concurrently co-exists in the same area, leading to improved network capacity and better spatial reuse of the radio spectrum.

It is also desirable to provide a power control system and method designed for mobile ad-hoc networks, which system and method can be used with a variety of media access control algorithms for nodes sharing a common transmission channel.

Although the invention is described here in the context of ad hoc networks, a person skilled in the art should be able to apply the techniques of this invention to other types of wireless communication networks as well.

SUMMARY OF THE INVENTION

It is an object of the present invention to allow nodes in the network to estimate a power level to use for transmitting to a particular node before the transmission and to adjust the value of the power level as transmitting conditions change. One of the ways of implementing such an objective is to make each node use a particular power level for each destination. In other words, a node uses different transmission power level when transmitting to different neighbors. In order to do so, each node maintains a power cache, where the power level information is stored. A power cache, where the power

level for a neighbor node is stored, is a double entry table; it is indexed by the identification of the node and contains the estimated power to be used for transmission to that neighbor node. When a source node transmits to a destination node not found in the power cache, the source node will use the maximum transmission power to transmit to that destination; i.e., the maximum power level is entered in the cache in the corresponding row.

Nodes gather power level information every time they receive a packet, even if the packet is not addressed to them (due to the broadcast nature of the wireless communication and the use of a common channel, transmission by one node will reach all of the nodes in the network). Such an operation is commonly referred to as *eavesdropping*. Of course, the node does not need to process the transmission not destined to it; rather it needs only to evaluate the power of the transmission. Each packet has a special field containing the value of the power level used to transmit that packet. When nodes receive a packet, they measure the actual power level of the received signal, for instance, through a mechanism such as the Received Signal Strength Indicator (RSSI). The nodes then can use the values of the transmitted and received power levels to calculate the path loss.

The power level control techniques of the present invention comprise two basic embodiments. In the *first* embodiment, the path loss between the sending node *A* and the receiving node *B* is calculated at the receiving node *B*. Based on the path loss information, the power level to be used in the reverse direction (i.e., from node *B* to node *A)* is then determined and entered in the cache of node *B*. In the *second* embodiment, the path loss between the sending node *A* and the receiving node *B* is calculated at the receiving node *B* and the calculated information is used to determine the required transmission power from node *A* to node *B*. This power level is then *conveyed* on the reverse channel back to node *A*, which stores this information in its cache for use in future transmissions to node *B*.

We first describe the operation of the power level control technique of the present invention based on the *first* embodiment. The power level control technique comprises frame transmission and power cache maintenance. As illustrated in Fig. 2, the process of building a power cache comprises the following steps: when a frame arrives at a receiving node (20), the receiving node reads the value of the power level encoded in the frame (22) and uses that determined power level to calculate the power level to be

used for the next transmission to the sending node (24). Once the power level has been calculated, the node checks if there is a previously stored power level value corresponding to that sending node in the power cache (26). If there is a previous value stored in the cache, then the node overwrites it with a newly calculated power level value (28). If no power level value corresponding to that sending node is stored in the cache, then the node writes in the calculated value (30).

In a simple version of this embodiment, the power level of the received signal is stored in the power cache of the receiving node. The rationale of such an algorithm is that if the receiving node is able to receive data from the source node at a particular power level, then the same level used for transmitting data to that source node will be sufficient.

In another version of the embodiment the relationship between the received power level and the power level threshold of the receiving node are factored into calculating the power level corresponding to the sending node to be stored in the cache. A value too close to the threshold can be insufficient due to some unknown fading a signal might encounter during the transmission. Moreover, since the nodes in the network are mobile, a particular node may become unreachable for a close-to-threshold value of the power level. To calculate the appropriate power level for transmitting to a destination node, one can assume that the path loss L_{AtoB} in both directions in a reciprocal transmission channel is the same:

$$L_{AtoB} = P_{A.tx} - P_{B.rx} \tag{1}$$

According to equation (1), the total path loss of a transmission from node *A* to node *B*, L_{AtoB}, includes not only the path loss due to attenuation, but also due to fading. The value of L_{AtoB} is obtained by subtracting the received power measured at receiving node *B*, $P_{B.rx}$, from the transmitted power used by the sender *A*, $P_{A.tx}$, wherein the value of the transmitted power $P_{A.tx}$ is encoded as a control field in the transmitted packet.

To make sure that node *B* chooses a sufficient value of the power level to store in the power cache entry corresponding to node *A*, the calculation of that power level should result in a value higher than the receiver's threshold. For example, to make sure that statistical variations of the power level do not affect the quality of the transmission between the nodes, the required transmission power from *B* to *A* is calculated by a node in accordance with equation (2):

$$P_{BtoA} = \min(L_{AtoB} + T + 1.5\,\sigma^2, P_{max}) \quad (2)$$

where T is the receiver threshold (i.e., the minimal acceptable received power) and P_{max} is the maximal transmission power, limited by the nodal hardware. σ^2 is the variance of the fading, and it is either estimated or known in advance as a parameter of the communication channel. Equation (2) helps in selecting a value that does not raise the power level above the receiver's threshold too much, but at the same time factors in the fading conditions.

Fig. 3 refers to a power cache building algorithm implemented in one of the embodiments of the present invention. According to that algorithm, when a frame arrives at a receiving node (32 in Fig. 3), the power level value used at transmission encoded in the frame is read by a receiving node (34). The receiving node reads the encoded power level value and also measures the power level value of the received signal for calculating the total path loss (36). Then the receiving node either stores the received power level value in its power cache for future transmissions to the sending node (38) or uses equation (2) to calculate the power level to use for future transmissions (39) and stores it in the power cache. Note, that in some cases, averaging old values of power levels with the currently measured value may be recommended. In such cases, the power cache may store previously used values, which will be used with some weightings in an averaging function.

In the *second* embodiment of the invention, the required power level is determined by the destination of the transmission and is "piggybacked" on a packet going in a reverse direction. Thus, for instance, if node *A* transmits to node *B*, node *A* includes in the packet header the transmitted power. Node *B* then calculates the path attenuation based on equation (1) by measuring the received power level. It then uses equation (2b)

$$P_{AtoB} = \min(L_{AtoB} + T + 1.5\,\sigma^2, P_{max}) \quad (2b)$$

to calculate the required transmission power from *A* to *B*, given the node *B*'s receiver threshold T. This required power is then conveyed to node *A*, which stores the value as

its power cache entry that corresponds to node B and will use it on its next transmission to B.

Using one or another embodiment of the present invention, a network node ready to transmit a packet checks its power cache to read the previous power level value corresponding to the destination node, as denoted by 50 in Fig. 4. If such a value is available, the node adjusts the transmitter power level to the recorded power level value and transmits the packet at that power level using some wireless MAC algorithm (52). If no recorded for that destination is stored in the power cache, then the node transmits at the maximum power level (54).

All the packets transmitted in the network contain an encoded value of the transmitting node's power level, so when a node receives a packet, it can read the transmitter's power level. Plus, the receiving node measures the power level of the incoming packet. Based on the power level of the incoming packet, the encoded transmitter's power level and a channel fading parameter, the receiving node calculates the power level to be used for future transmissions. This value can be either communicated to the sender on the reverse channel, or could be used by the receiving node in its future transmission back to the sender. In the latter case, it is assumed that the channel in both directions has similar propagation characteristics. Whatever the power determination algorithm is used, the calculated value is then stored in the cache of the corresponding node for future use.

DETAILED DESCRIPTION OF THE INVENTION

Before describing the adaptive power control algorithm in detail, some relevant features of wireless communication should be described. As with wired signal transmission, the signal strength (power) decreases (attenuates) as the signal travels away from the transmitter. In a practical radio propagation environment, the attenuation is proportional to some power of the distance, usually between 2 and 6. For noise- and interference-limited systems, the power level of a signal should be above a certain minimum power level (threshold) for a receiver to receive the signal and to ensure satisfactory quality (BER – Bit Error Rate) of the detected signal. This condition usually limits the maximum distance between a transmitter and a receiver. Wireless transmission is also subject to fading. Two fading mechanisms are most common: multi-path fading, which leads to what is commonly known as short-term fading, and

shadow fading, caused by natural and man-made obstructions. Fading produces a time varying component in the power of the received signal, which sometimes leads to a complete loss of a signal and, consequently loss of one or more data packets. Moreover, if more than one transmission occurs simultaneously, all the colliding transmissions will be most often destoyed. However, under some circumstances one of the transmissions can succeed if it is received with a significantly higher power level than the sum of the power levels of the other transmissions. This is called the capture effect, in which the receiver "captures" the signal because it is much stronger than the background interference. Capture usually increases the throughput of a network.

The type of objectives and challenges in wireless networks in general and in media access control schemes in ad-hoc networks in particular is different from those in the wired networks. Although a node in a wireless network can still check the availability of the channel before transmitting, it cannot do this during the actual transmission due to a significant dynamic range of the transmitted and received signals. Thus, CSMA/CD protocol is hard to use, although CSMA remains a suitable option. However, the problem with the use of the CSMA scheme is the so-called *hidden*- and exposed-terminal problems. When two (or more) nodes are in the range of a third node, but not in range of each other, they are subject to the hidden terminal problem.This means that simply sensing the availability of the channel will not properly indicate whether the channel is busy at the receiver. Thus, even though the nodes sense the channel as available, collisions are still possible. The hidden terminal problem allows nodes to transmit, when in fact they should defer.

The exposed terminal problem prevents nodes from transmitting when the channel is available and the nodes could transmit without interfering with other nodes' transmissions. Consider four (or more) nodes in a row and in this order: A, B, C and D that use some variation of the CSMA (Carrier Sense Multiple Access) MAC protocol. Suppose C transmits to D. B is prevented from communicating with A, since it can sense C's transmission. Node B thus is an exposed terminal. That is, although B could transmit to A without interfering with the ongoing transmission from C to D, as B senses C's transmission, B unnecessarily defers.

Some wireless MAC schemes use the Collision Avoidance algorithm. The basic idea is to inform the neighbor nodes that a particular transmission is going to take place and that collisions should be avoided. To avoid collisions, the source node sends the

destination node a very short Request To Send (RTS) control packet before transmitting actual data. This RTS packet is answered by the destination node with another short Clear To Send (CTS) packet. After correctly receiving the CTS packet, the source node is then allowed to transmit the data packet. All the nodes in the neighbor of the two communicating nodes will listen to the RTS/CTS dialog and will defer from accessing the channel, thus, avoiding collisions. (However, since collisions can still occur, the RTS/CTS dialogue reduces, rather then eliminates collisions.)

Fig.1 is an example of an ad hoc network 10 with a number of nodes 12. The dotted line 14 represents the transmission range of node 12'. Lines 16 connecting node 12' to nodes12a, 12b and 12c represent the neighboring relationship between node 12' and nodes 12a, 12b and 12c, which are closer to node 12' than the transmission range R. In ad hoc network 10 a node can communicate directly only with its neighbors. Every transmission between two neighbors is called a hop. When a node wants to send a packet to another node, which is not its neighbor, other intermediate nodes will forward the packet until the final destination is reached. Therefore, ad-hoc network 10 provides for two different kinds of connectivity: one-hop connectivity and multi-hop connectivity. One-hop connectivity (C_1) corresponds to the number of neighbors of a node:

$$C_1 = \frac{\sum_{i=1}^{N} neig(i)}{N(N-1)} \qquad (3)$$

Where N is the number of network nodes and $neig(i)$ is the number of neighbors of node i.

Multi-hop connectivity takes into account the mean number of nodes that can be reached from each node either directly or indirectly. We define multi-hop connectivity C_m as follows:

$$C_m = \frac{\sum_{i=1}^{K} nodes(i)(nodes(i) - 1)}{N(N-1)} \quad (4)$$

where *nodes(i)* is the number of nodes of cluster *i*, and *K* is the total number of clusters in the network. A cluster is a set of nodes where none of them has any neighbor outside of the cluster. When the network is divided in two or more clusters we say that the network is *partitioned*. While some reduction in local network connectivity is not necessarily a problem for MAC algorithms (it can even lead to improvements in network capacity, as more concurrent transmissions become possible), total loss of connectivity, as in network partition, is undesirable in any type of networks. Therefore, to ensure that packets can be delivered to the destination, network partitions should be avoided and the high degree of multi-hop connectivity (C_m =1) is needed.

Since most of the current wireless MAC networks are using some variation of the RTS/CTS approach (Request-To-Send/Clear-To-Send) to address the exposed- and hidden-terminal problems, it seems to be a good choice to apply the power adjusting techniques of the present invention to the current MAC networks. In a MAC network each transmission of data between a source node and a destination node calls for a number of different frame transmissions. To illustrate the invention, refer to Fig. 5, where a node preparing to transmit data waits for the idle channel (60) and then sends a short RTS frame to the destination node (62). The RTS frame contains a field indicating the length of the data packet ready to be transmitted.

When the destination node receives the RTS frame, it sends back to the source node a short CTS frame as an acknowledgement (66). When the source node receives the CTS frame, it starts transmitting the data (70). Any network node, which is neither a source node nor destination node, receives the RTS/CTS exchange, but does not transmit data. It is important to note that when the destination node receives the RTS frame at

step (64), the destination node calculates the power level to be used for future transmissions either to the source node, as in the *first* embodiment of the invention, or to the destination node, as in the *second* embodiment. This value of the power level is then stored in the power cache of either the destination node, as in the *first* embodiment of the invention (and is used to control the power of the CTS packet to be sent next from the destination to the source), or in the power cache of the source node (after being conveyed from the destination node to the source node using the CTS packet), as in the *second* embodiment of the invention. In the *second* embodiment of the invention, the source node receiving the CTS frame (68) calculates the power level, stores it in its cache and adjust its power level accordingly.

When a node calculates the value of the power level to store in the cache, it reads the power level used by the transmitter (40 in Fig. 6), determines the power level of the received signal (42), calculates the total path loss (44) and then calculates the required power level value for using equation (2) other suitable technique (46).

Note that a hybrid scheme incorporating both of the embodiments of the invention is possible as well; in other words, the destination node, after receiving the RTS packet and measuring its power, calculates the power of the transmission in the reverse direction (as in the *first* embodiment of the invention) and then using this power, transmits in its CTS packet the power that the source node should use in its future transmissions (such as the data packet itself) to teh destination node.

With the above hybrid power control technique of the present invention the power level of both source and destination nodes can be adjusted during the RTS/CTS exchange. The source node is unlikely to use its maximum power level for data transmission unless it sends to the broadcast address, because even if the destination node power level is not stored in the source node's cache, the source node will receive that power level value in the CTS frame. It means that use of maximum power will happen at the initial RTS frame transmission step only, because for the CTS and the subsequent data transmissions, the nodes will be able to use adjusted power levels. The power saving technique will also apply to the case when a station in a MAC network works only as a receiver, but not as a transmitter, assuming that the receiver-only node sends back some kind of an acknowledgment to the sending nodes.

In what follows, we present performance evaluation of a wireless ad hoc network with a power control technique. The evaluation is based on estimating the distance between a node and its neighbors. Neighbor nodes are all the nodes that are closer to the node than a certain maximum transmission range R. To determine the distance from a certain node to its neighbors, we assume a uniform distribution of neighbor nodes around the node and throughout the covered area. The probability of finding a neighbor within a particular transmission range *k* is given by equation (5):

$$P(x \leq k) = \frac{k^2}{R^2} \qquad (5)$$

The PDF (Probability Distribution Function) of the distance between the node and a neighbor is given by:

$$f(x) = \frac{2x}{R^2} \qquad (6)$$

Thus, the average value of the distance to a node's neighbor can be calculated as:

$$E[f(x)] = \frac{1}{R^2}\int_0^R 2x^2\,dx = \frac{1}{R^2}\left[\frac{2x^3}{3}\right]_0^R = \frac{2}{3}R \qquad (7)$$

The reduction of the transmission range is advantageous when it leaves enough "unused space" that eventually can be used by other concurrent transmissions. The higher the number of concurrent transmissions is, the higher is the network capacity, which is here normalized to the packet transmission time. An approximate concurrence level *X* for a certain transmission range *R* can be estimated as a number of simultaneous transmissions that can take place in a bounded area *A*:

$$X = \frac{A}{\pi R^2} \qquad (8)$$

To evaluate the concurrence level of the power-controlled network, the value of the transmission range given by equation (7) is used:

$$X = \frac{A}{E[\pi x^2 f(x)]} = \frac{A}{\pi \int_0^R x^2 \frac{2x}{R^2}\, dx} = \frac{A}{\frac{\pi R^2}{2}} \qquad (9)$$

Comparing the non power-controlled network (transmission range of R) with the power-controlled network (transmission range of 2/3 R), the following expected improvement in concurrency (and, correspondingly, in network capacity) can be obtained:

$$T_{improvement} \propto \frac{X}{X'} = \frac{\pi R^2}{\frac{\pi R^2}{2}} = 2 \qquad (10)$$

As follows from (10), the improvement can be as high as twice the capacity of the network.

To estimate the power savings provided by a power controlled network, the starting point is a consideration that in an ideal propagation model the losses of power happen only due to path attenuation. For a given transmission range *R*, a power level P_{tx} will allow to achieve successful transmission with high probability:

$$P_{tx} = KR^{\beta} \qquad (11)$$

In equation (11), parameter β represents the propagation exponent, which is dependent on the environment where the transmission takes place. Parameter β usually ranges from 2 to 6. *K* is a constant and *R* is the transmission radius. To calculate the power saved, we use the following expression:

$$P_s = 1 - \frac{P_{\text{power control}}}{P_{\text{normal}}} \qquad (12)$$

It follows from (12) that the values of power savings P_s range between 0 and 1, where 0 means no saving at all, and a 1 value means no power consumption (unachievable value).

For the power controlled technique of the present invention the power savings are as follows:

$$P_s = 1 - \frac{K(2R/3)^{\beta}}{KR^{\beta}} = 1 - (2/3)^{\beta} \qquad (13)$$

The power savings are dependent on the propagation exponent. The larger the propagation exponent is, the more power savings one can expect:

Exponent	Power Saving
2	56%
3	70%
4	80%
5	87%
6	91%

Thus, by using the power control scheme of the present invention, we can expect a reduction in power consumption of more than half of the non power-controlled case, while doubling the network capacity.

Of course, one should see the discussion above as exemplary only; there are many other possible applications of the present invention.

Two examples of performance comparison of different MAC protocols (CSMA and DBTMA) with the power control technique of the present invention are provided below.

Power control in CSMA

CSMA simulations were performed on a square of 500 length units by 500 length units, with 25 nodes spread at random (two-dimensionally, uniformly), and remaining in the same location throughout the simulation period. Two experiments with different values (500 and 150 length units) for a maximum transmission range R were performed, wherein the value of R in both cases was selected sufficiently large to ensure the maximum multi hop connectivity of $C=1$.

The same network traffic (offered load) for CSMA with and without power control was used and it was assumed that the nodes don't move during the simulation and that the values of transmission power in the power caches at each node were initially correctly set, so that no transit behavior was experienced.

Fig. 7 shows the result of the simulation for R=500. The network capacity shown in the graphs is the normalized network capacity. The network capacity of 1 means that the network delivers one data packet during a data packet transmission interval. Because in these networks concurrent transmissions can take place, the capacity can be higher than 1. With R=500, only one successful transmission can take place at the same time, because all of the simulation area is used by the sender and any concurrent transmission will lead to a collision. However, as seen in Fig. 7, with the power control algorithm, only a fraction of this area is used, allowing several concurrent transmissions. Therefore, the implementation of the power control technique leads to a much higher network capacity resulting from these concurrent non-colliding transmissions.

For a low load, both curves in Fig. 7 exhibit similar behavior. However, as the load increases, the regular CSMA network with no power control reaches its saturation point beyond which the network capacity is essentially zero. But the power-controlled CSMA exhibits a higher capacity for a wide range of the offered load, reaching a maximum capacity of 0.62, compared to the maximum of 0.53 in non power-controlled network. Note that because this simulation assumes a finite population of nodes, the simulation results may not match exactly the results of the analytical calculations

provided above, because the analytical results are based on an infinite population of nodes.

Fig. 8 represents the simulation results of the same network with the maximum transmission range of 150 length units. As can be seen in Fig. 8, a smaller transmission range results in a better network capacity of 2.01 for the regular CSMA with no power control, which is explained by the fact that a smaller transmission range leads to the reduction in the number of collisions and, therefore, to a better spatial reuse. In this case, the advantages of the power control are smaller, as compared with the case of a larger maximum transmission range. When the maximum transmission range is close to the optimum value, the power control technique does not lead to a significant improvement, since with the smaller transmission range, the distribution of the neighbor nodes is no longer uniform. The optimum value for the transmission range is considered as the lowest transmission range that still provides a multi-hop connectivity of 1.

Power control in DBTMA

As noted previously, the CSMA algorithm may not be the best choice for wireless networks. Several variants of collision avoidance algorithms have been developed, all of them based on the idea of combining CSMA with a control dialog to try to overcome the hidden- and the exposed-terminal problems and to reduce the number of collisions.

One of these algorithms is the *Dual Busy Tone Multiple Access (DBTMA)* that includes an RTS/CTS dialog before the beginning of the data transmission, together with two busy tones that are sent during the data transmission and reception over a secondary control channel. This algorithm requires the use of two different channels, one of which is a broad data channel and the other one is a narrow control channel used for transmitting the RTS/CTS packets and also for sending busy tones. When a node is transmitting a data packet, it is also sending the transmitter busy tone. When a node is receiving a data packet, it is also sending the receiver busy tone on the control channel.

As can be seen in Fig. 9, the network capacity of the DBTMA is limited to the maximum capacity of 1 in the non power-controlled network, because no more than one simultaneous transmission can take place. By adding the power control feature to the DBTMA algorithm, the network performance improves significantly, yielding more than 4.5 times of its previous capacity. This is the result of the fact that each power

controlled transmission uses a much smaller area, allowing other concurrent transmissions to occur. Although the power-controlled network exhibits some degradation at the higher offered load region, the original improvement is big enough to continue to maintain advantage over the non power-controlled version.

Next, the DBTMA simulation with lower maximum transmission range is shown. Again, the power controlled DBTMA provides better network capacity for all the range of loads, as shown in Fig. 10. However, the improvement is only about the 25% and not the 450% that was observed in Fig. 9.

The same network behavior is shown in the non power-controlled CSMA case in Fig. 8. The lower the transmission range is, the lesser is the benefit provided by the power control scheme. However, even at small values of the maximum transmission range, the power control scheme still provides higher network capacity, as compared with the network with no power control case.

Measured Power Savings

As it was shown by the analytical calculations and simulations, the power saving of the power control scheme in a network is dependent on the propagation exponent determined by the surrounding environment. To estimate the power savings resulting from the implementation of the technique of the present invention, it is assumed that the propagation exponent is 3. The expected power savings obtained by the power control scheme are about 1.5 times more than the increase in the network -capacity. (The saving is the same when the value for the propagation exponent is 2). The power savings corresponding to various transmission ranges for CSMA and DBTMA algorithms are presented below:

CSMA, R=150	50.00%
CSMA, R=500	80.00%
DBTMA, R=150	55.00%
DBTMA, R=500	83.00%

It is noted that in practice the power savings may be slightly lower due to, for example, the mobility of the nodes and inaccurate cache updates.

It is therefore evident from the above provided description that significant improvements of the performance of a wireless network can be achieved by implementing the adaptive power control scheme focusing on the reduction of the transmission power and the increase of network capacity. The simulation results show that a significant improvement of these two parameters can be achieved through the use of the disclosed power control scheme. The obtained power savings of 50% or better were demonstrated while increasing the network capacity from about 20% to more than 400%, depending on network parameters. The usage of power for memory or processing turns out to be negligible. Furthermore, because nodes store and later use information about their neighbors only, the power control technique scales well with the size of the network. Since the power control technique provides the same level of one-hop connectivity as would be achieved without it, no increased probability of network partition is present.

What is claimed is:

1. A wireless communication network comprising a plurality of mobile nodes, the network comprising:

source data containing a value of a first power level;

a source node transmitting the source data to a destination node at the first power level; and

the destination node receiving the source data, reading the value of the first power level from the source data and storing the value of the first power level in a destination node cache.

2. The network of Claim 1, further comprising destination node data transmitted from the destination node to the source node at the first power level read from the destination node cache.

3. The wireless network of Claim 1,wherein the destination node cache containes stored power level values for the plurality of mobile nodes.

4. The wireless network of Claim 2, wherein the source data are a request-to-send type frame and the destination node data are a clear-to-send type frame.

5. The wireless network of Claim 1, wherein the wireless network is an ad hoc network.

6. The wireless network of Claim 1, further comprising a source node cache.

7. A wireless communication network comprising a plurality of mobile nodes, the network comprising:

source data containing an encoded value of a first power level;

source node transmitting the source data to a destination node at the first power level; and

the destination node receiving the source data, reading the encoded value of the first power level from the source data, measuring a received power level of the source

data, calculating a second power level using the first power level and the received power level of the source data, and storing the second power level or a function of the second power level in a destination node cache.

8. A wireless communication network comprising a plurality of mobile nodes, the network comprising:

source data containing an encoded value of a first power level;

a source node transmitting the source data to a destination node at the first power level; and ;

the destination node receiving the source data, reading the encoded value of the first power level from the source data, measuring a received power level of the source data, calculating a second power level using the first power level and the received power level of the source data, and conveying the second power level to the source nodefor storing the second power level or a function of the second power level in a source node cache.

9. The wireless network as in Claim 7, further comprising destination node data being transmitted from the destination node to the source node at the second power level read from the destination node cache.

10. The wireless network as in Claim 8, further comprising source node data being transmitted from the source node to the destination node at the second power level read from the source node cache.

11. The wireless network as in Claim 7, wherein the destination node calculates a total path loss which is used to calculate the second power level.

12. The wireless network as in Claim 8, wherein the destination node calculates a total path loss which is used to calculate the second power level.

13. The wireless network of Claim 7, wherein the source data are a request-to-send frame.

14. The wireless network of Claim 8, wherein the source data are a request-to-send frame.

15. The wireless network of Claim 9, wherein the destination node data are a clear-to-send frame.

16. The wireless network of Claim 10, wherein the destination node data are a clear-to-send frame.

17. A method of adjusting transmission power in a wireless network comprising a plurality of mobile nodes, the method comprising:

broadcasting a first short frame by a source node;

receiving the first short frame by a destination node, calculating a source node transmission power level and storing the source node transmission power level in a destination node cache;

transmitting a second short frame by the destination node at the source node transmission power level; and

receiving the second short frame by the source node, calculating a destination node transmission power level, storing the destination node transmission power level in the source node cache and transmitting data from the source node to the destination node at the destination node transmission power level.

18. A method of adjusting transmission power in a wireless network comprising a plurality of mobile nodes, the method comprising:

broadcasting a first short frame by a source node;

receiving the first short frame by a destination node andcalculating a source node transmission power level by the destination node;

transmitting a second short frame by the destination node, which second short frame contains information about the source node transmission power level;

receiving the second short frame by the source node, storing the information about the source node transmision power level in the source node's cache, calculating a destination node transmission power level, and transmitting a third frame containing the

information about the destination node transmission power level and the source node transmission power level to the destination node; and

receiving the third frame by the destination node and storing the information about the destination node transmission power in the destination node cache.

19. The method of Claim 17, wherein the wireless network is an ad hoc network.

20. The method of Claim 18, wherein the wireless network is an ad hoc network.

21. The method of Claim 17, further comprising determining a received power level of the first short frame, determining a power level of the source node used to transmit the first short frame, and using the received power level and the power level of the source node to calculate the source node transmission power level.

22. The method of Claim 18, further comprising determining a received power level of the first short frame, determining a power level of the source node used to transmit the first short frame, and using the received power level and the power level of the source node to calculate the source node transmission power level.

23. The method of Claim 21, further comprising using previously stored transmission power levels to calculate the source node transmission power level.

24. The method of Claim 22, further comprising using previously stored transmission power levels to calculate the source node transmission power level.

25. The method of Claim 17, wherein each node of the plurality of mobile nodes can serve as a destination node, as a source node or as a router.

26. The method of Claim 18, wherein each node of the plurality of mobile nodes can serve as a destination node, as a source node or as a router.

27. The method of Claim 17, further comprising the plurality of mobile nodes receiving the first short frame, calculating the source node transmission power level and storing the source node transmission power level in respective caches of the mobile nodes.

28. The method of Claim 18, further comprising the plurality of mobile nodes receiving the first short frame, calculating the source node transmission power level, conveying the source node transmission power to the source node, and storing the source node transmission power level in the cache of the source nodes.

29. A method of adjusting transmission power in a wireless network, the method comprising:

transmitting source data from a source node to a destination node, the source data comprising an encoded value of the source data power level;

receiving the source data by the destination node;

reading the encoded value of the source data power level;

storing the encoded value of the source data power level in a destination node cache; and

adjusting a transmission power level to the value of the source data power level by the destination node when transmitting destination data to the source node.

30. The method of Claim 29, further comprising transmitting destination data from the destination node to the source node at the source data power level.

31. The method of Claim 29, wherein storing the value of the source data power level comprises overwriting a previously stored power level value corresponding to the source node.

32. The method of Claim 29, wherein the wireless network is an ad hoc mobile network.

33. A method of determining a transmission power level value to be used to transmit data between a first node and a second node, the method comprising:

determining a first power level value used by the first node to transmit a first frame to the second node;

determining a received power level value of the first frame; and

using the first power level value and the received power level value to calculate the transmission power level value for transmitting data between the first node and the second node.

34. The method of Claim 33, further comprising storing the transmission power level value in a first node cache.

35. The method of Claim 33, further comprising storing the transmission power level value in a second node cache.

36. The method of Claim 33, further comprising calculating the transmission power level value as a function of the first and the received power level values and previously calculated power level values stored in the first node cache.

37. The method of Claim 33, further comprising calculating the transmission power level value as a function of the first and the received power level values and previously calculated power level values stored in the second node cache.

38. The method of Claim 33, further comprising using the first power level value and the received power level value to calculate a path loss and using the path loss to calculate the transmitting power level value.

39. The method of Claim 33, wherein determining the received power level value is performed by the second node.

40. The method of Claim 33, further comprising storing the calculated transmission power level value in a cache of a third node.

41. A wireless communication network comprising a plurality of mobile nodes, the network comprising:

source data containing an encoded value of a first power level;

a source node broadcasting the source data to the plurality of mobile nodes at the first power level; and

a destination node receiving the source data, reading the encoded value of the first power level from the source data, measuring a received power level of the source data, calculating a second power level using the first power level and the received power level of the source data, and storing the second power level or a function of the second power level in a destination node cache.

42. A wireless communication network comprising a plurality of mobile nodes, the network comprising:

source data containing an encoded value of a first power level;

a source node broadcasting the source data to the plurality of mobile nodes at the first power level; and

a destination node receiving the source data, reading the encoded value of the first power level from the source data, measuring a received power level of the source data, calculating a second power level using the first power level and the received power level of the source data, conveying the second power level or a function of the second power level to the source node, and storing the second power level or a function of the second power level in a source node cache.

43. The wireless communication network of Claim 41, further comprising the plurality of mobile nodes receiving the source data broadcast from the source node, measuring a received power level of the source data, calculating a second power level using the first power level and the received power level of the source data, and storing the second power level or a function of the second power level in respective caches of the mobile nodes.

44. The wireless communication network of Claim 42, further comprising the plurality of mobile nodes receiving the source data broadcast from the source node, measuring a received power level of the source data, calculating a second power level using the first power level and the received power level of the source data, conveying the second power level or a function of the second power level to the source node, and storing the second power level or a function of the second power level in the cache of the source node.

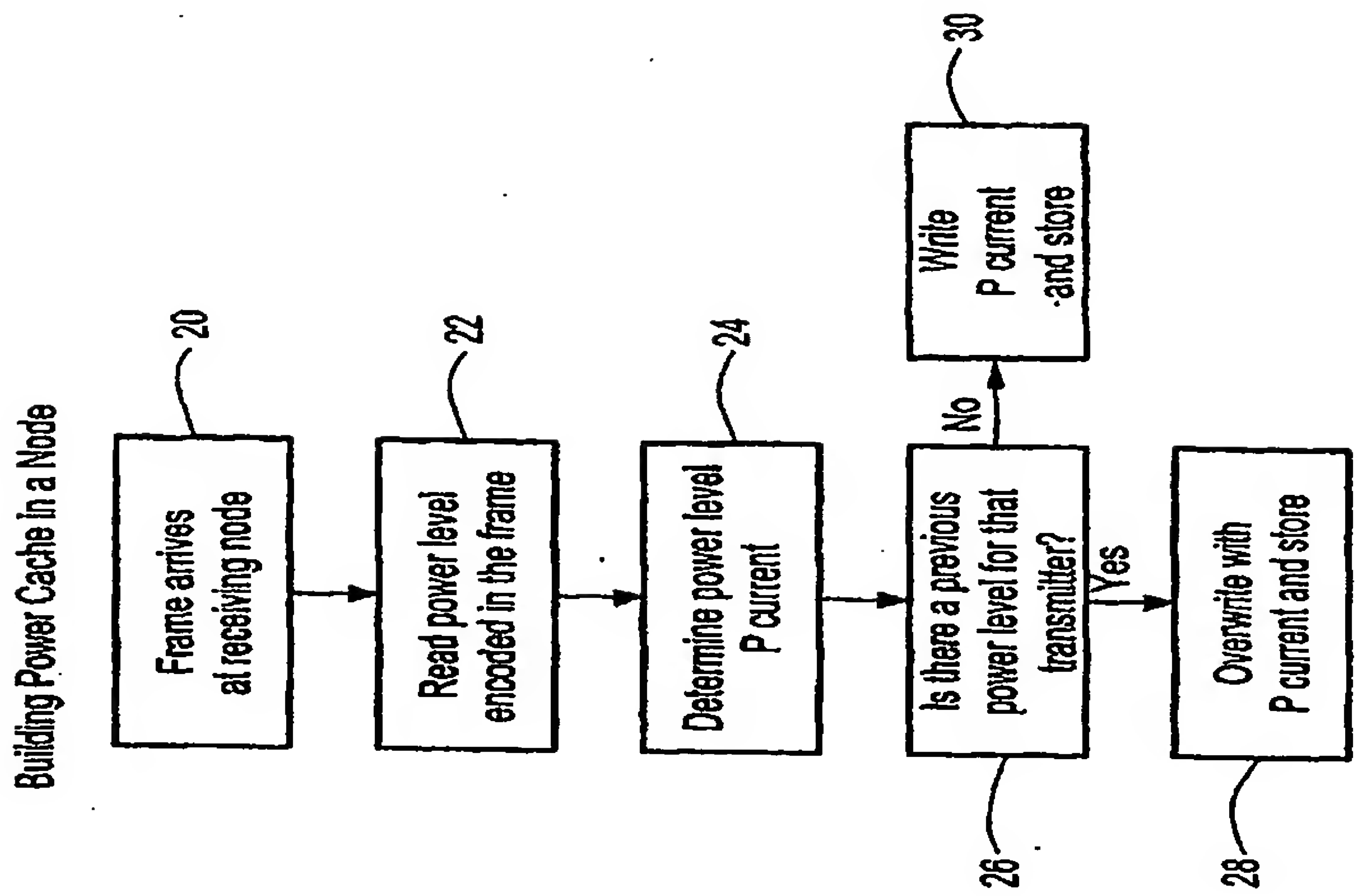

Building Power Cache in a Node
Frame arrives at receiving node
20
Read power level encoded in the frame
22
Determine power level P current
24
Is there a previous power level for that transmitter?
26
No
Write P current and store
30
Yes
Overwrite with P current and store
28

FIG. 2

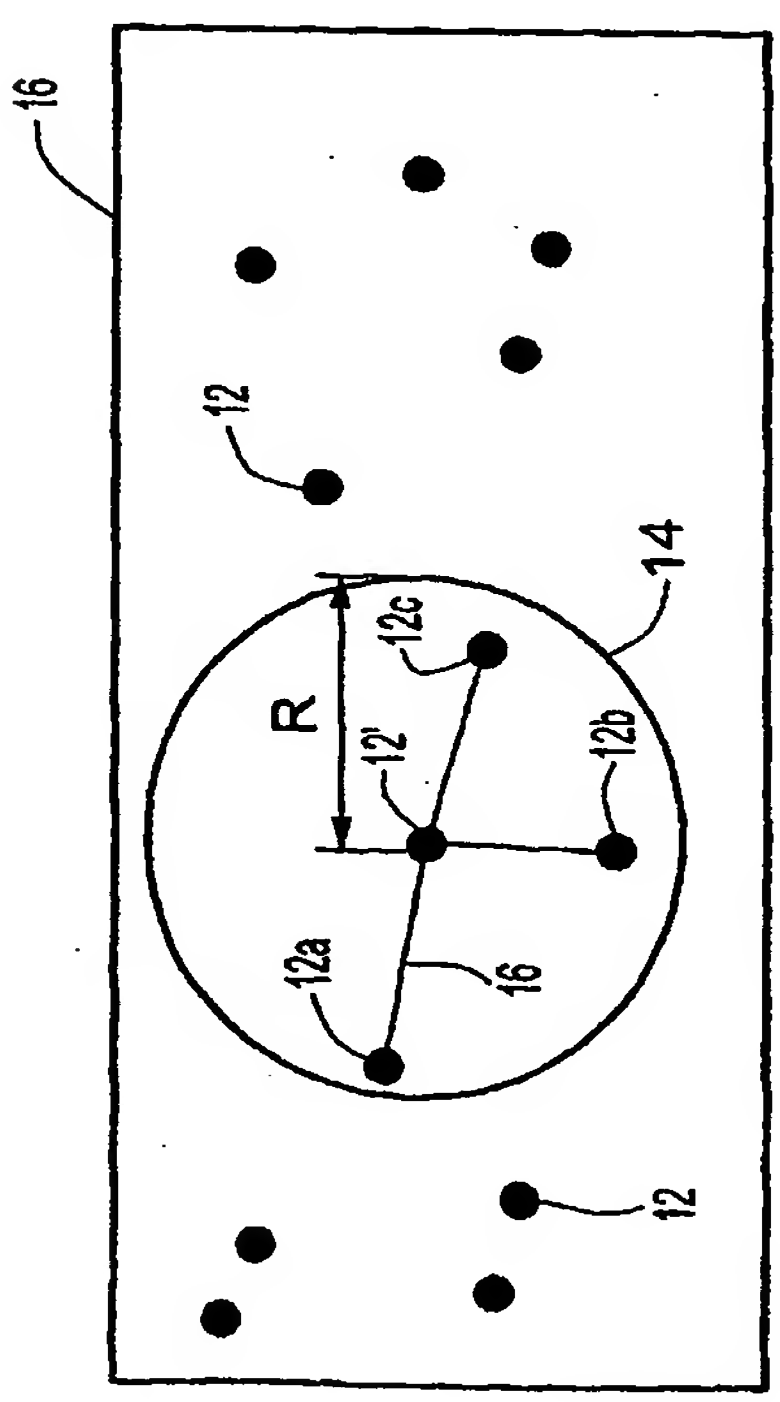
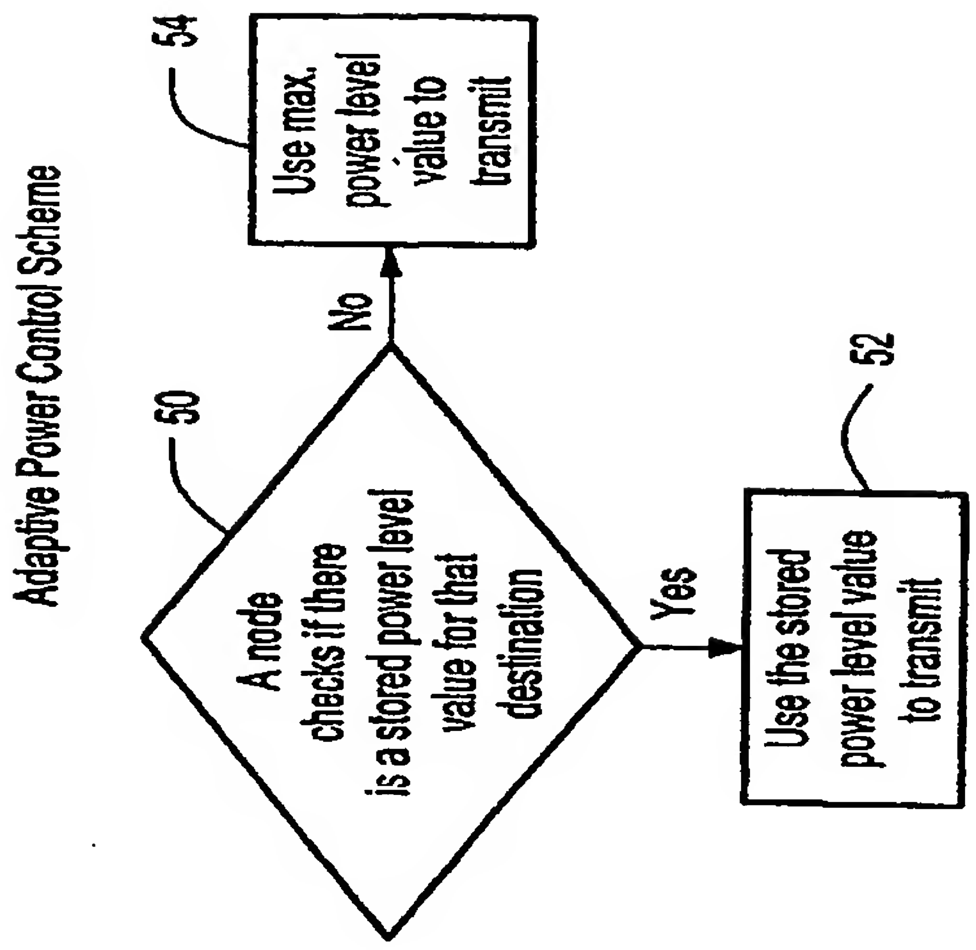
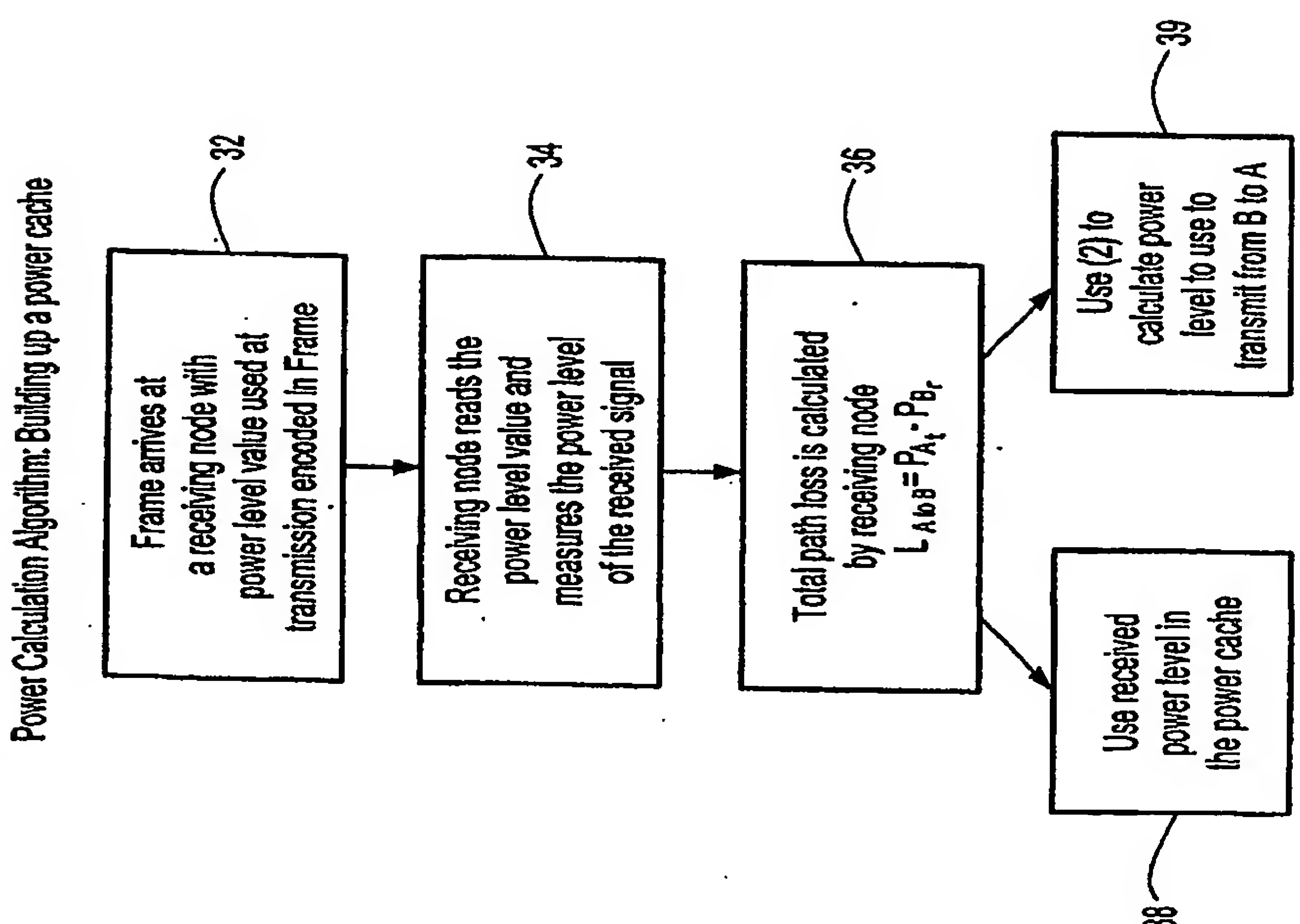

16
12
14
R
12c
12'
12b
12a
16
12

FIG. 1



Adaptive Power Control Scheme
A node checks if there is a stored power level value for that destination
50
No
Use max. power level value to transmit
54
Yes
Use the stored power level value to transmit
52

FIG. 4



Power Calculation Algorithm: Building up a power cache
Frame arrives at a receiving node with power level value used at transmission encoded in Frame
32
Receiving node reads the power level value and measures the power level of the received signal
34
Total path loss is calculated by receiving node $L_{AtoB}=P_{A_t}-P_{B_r}$
36
Use received power level in the power cache
38
Use (2) to calculate power level to use to transmit from B to A
39

FIG. 3

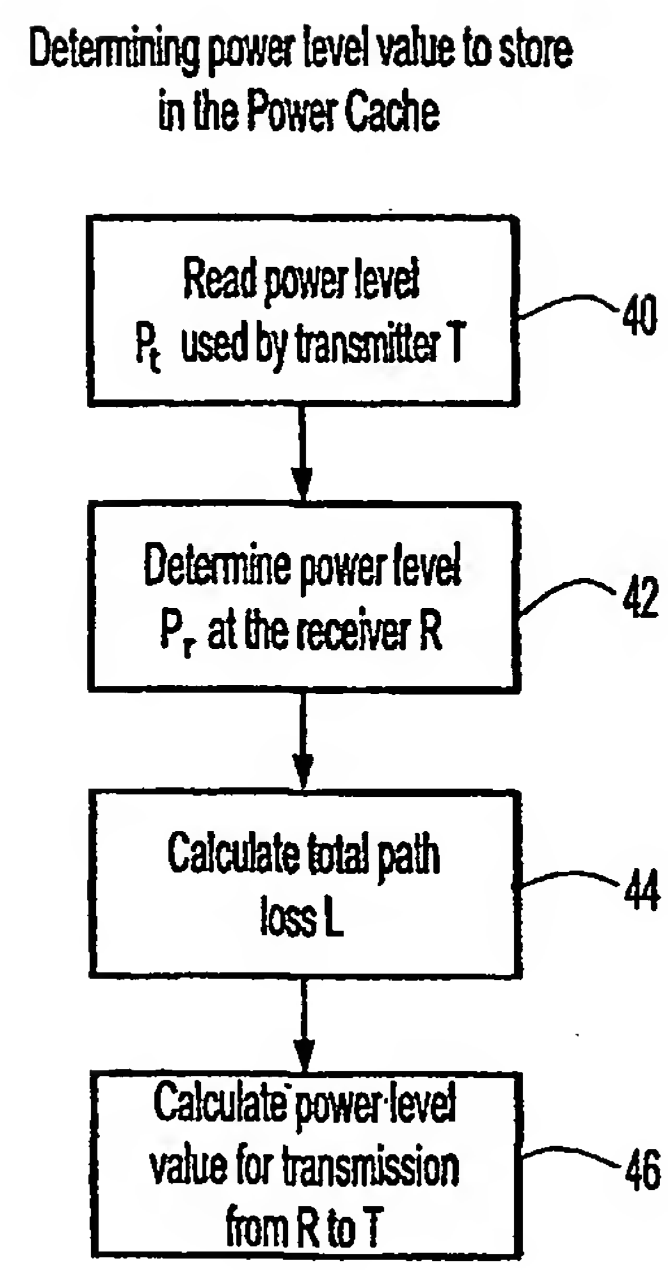

Determining power level value to store in the Power Cache
Read power level P_t used by transmitter T
40
Determine power level P_r at the receiver R
42
Calculate total path loss L
44
Calculate power level value for transmission from R to T
46

FIG. 6

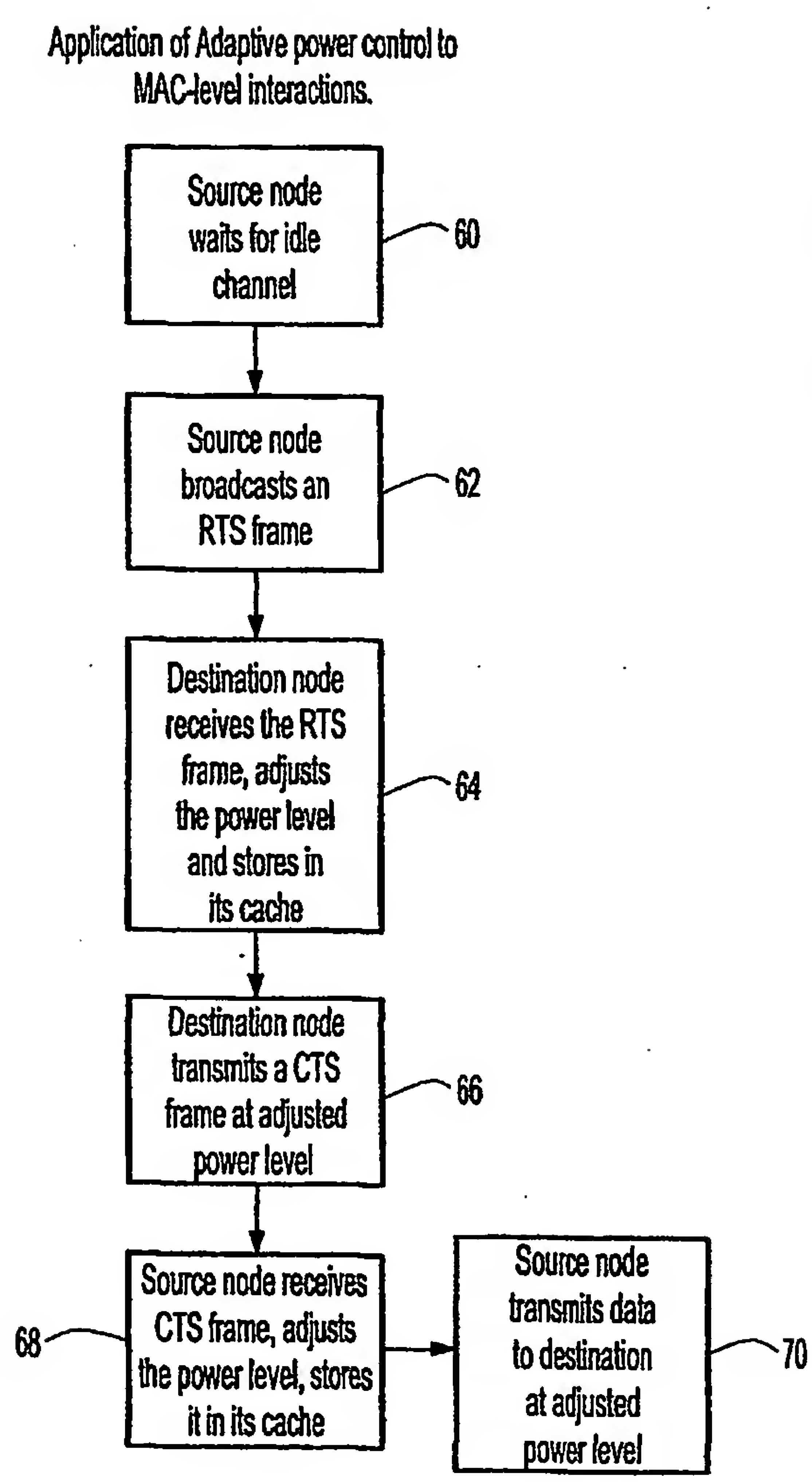

Application of Adaptive power control to MAC-level interactions.
Source node waits for idle channel
60
Source node broadcasts an RTS frame
62
Destination node receives the RTS frame, adjusts the power level and stores in its cache
64
Destination node transmits a CTS frame at adjusted power level
66
68
Source node receives CTS frame, adjusts the power level, stores it in its cache
Source node transmits data to destination at adjusted power level
70

FIG. 5

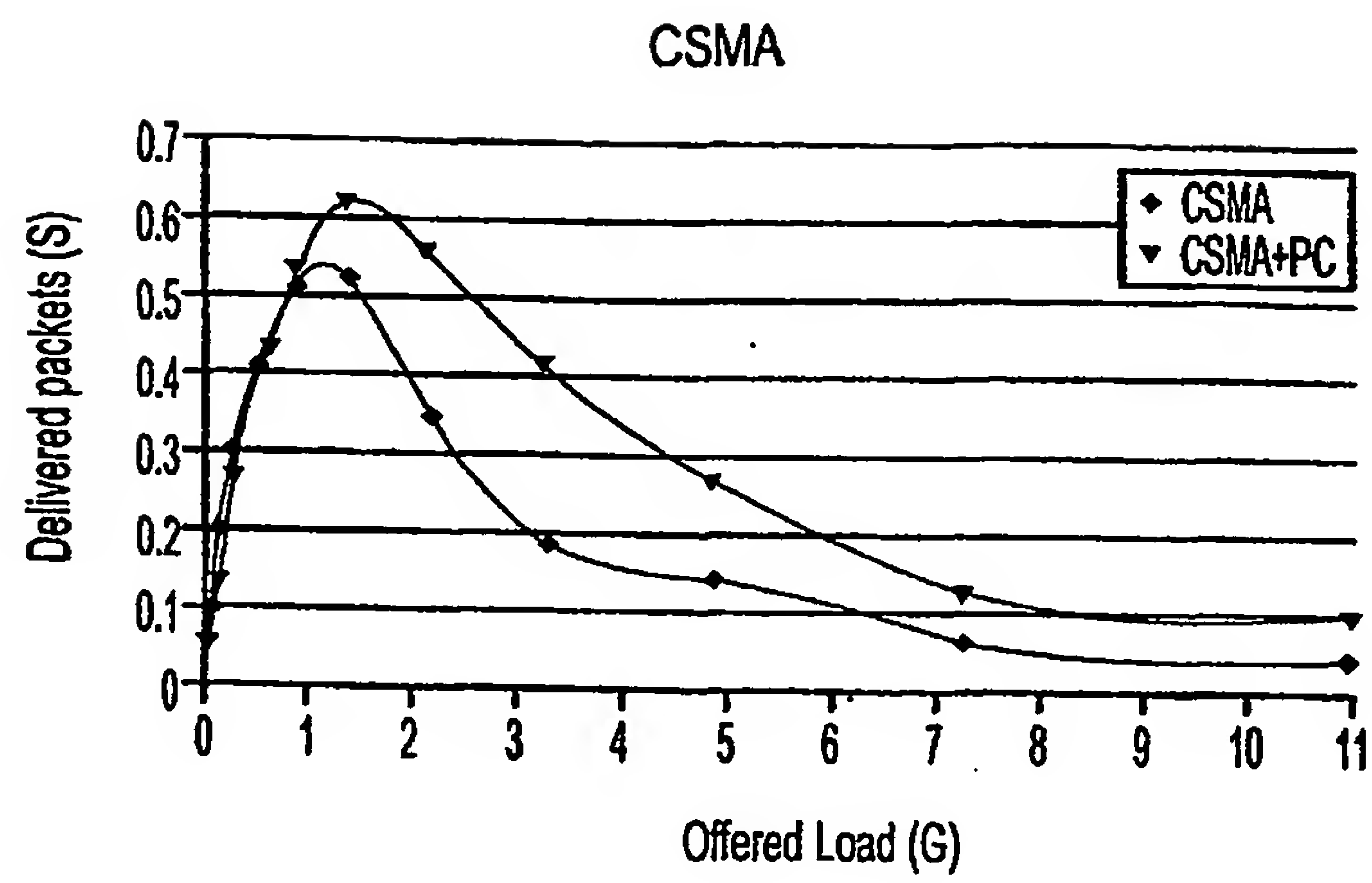

CSMA
Delivered packets (S)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
CSMA
CSMA+PC
0
1
2
3
4
5
6
7
8
9
10
11
Offered Load (G)

FIG. 7

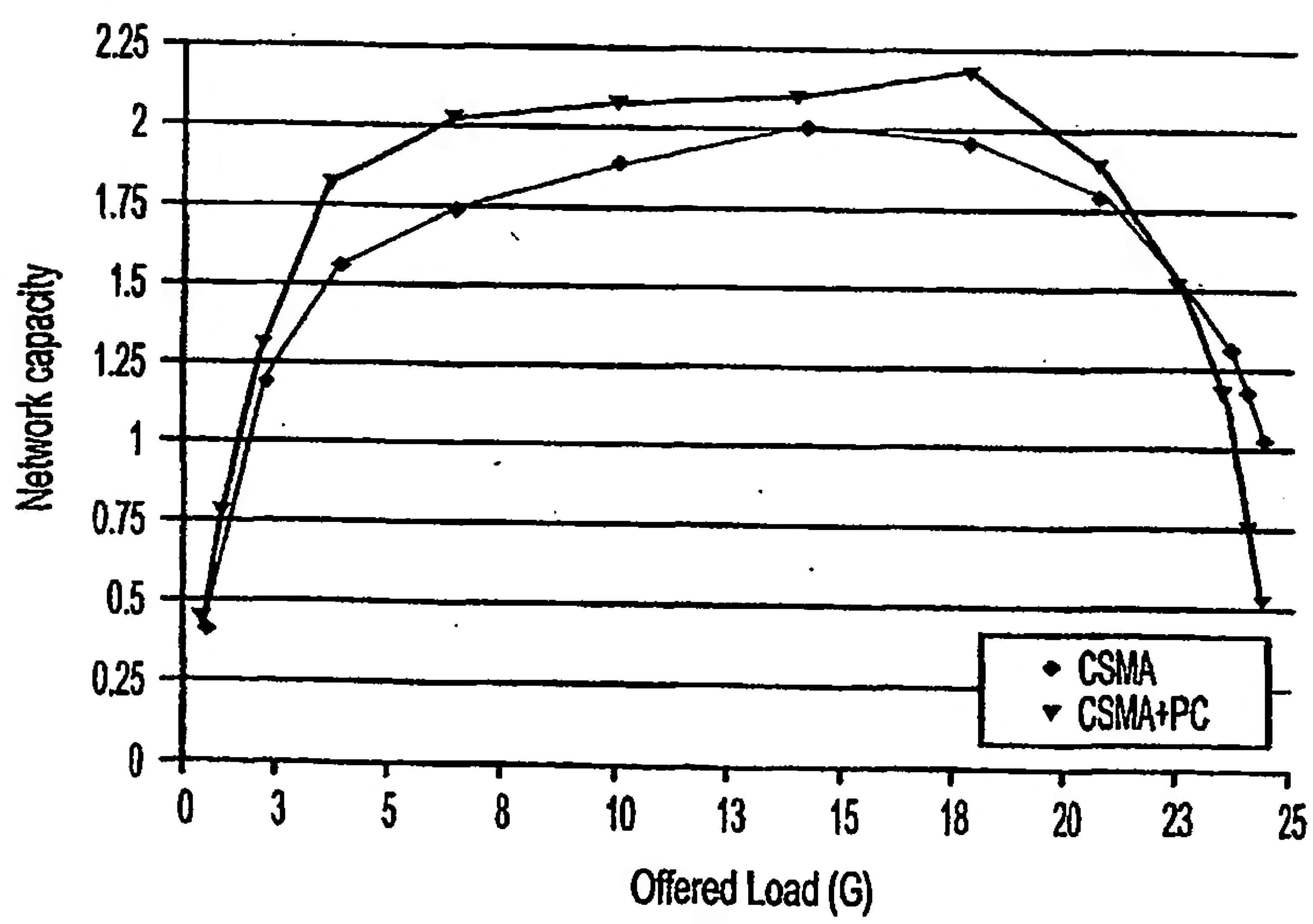

Network capacity
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
CSMA
CSMA+PC
0
3
5
8
10
13
15
18
20
23
25
Offered Load (G)

FIG. 8

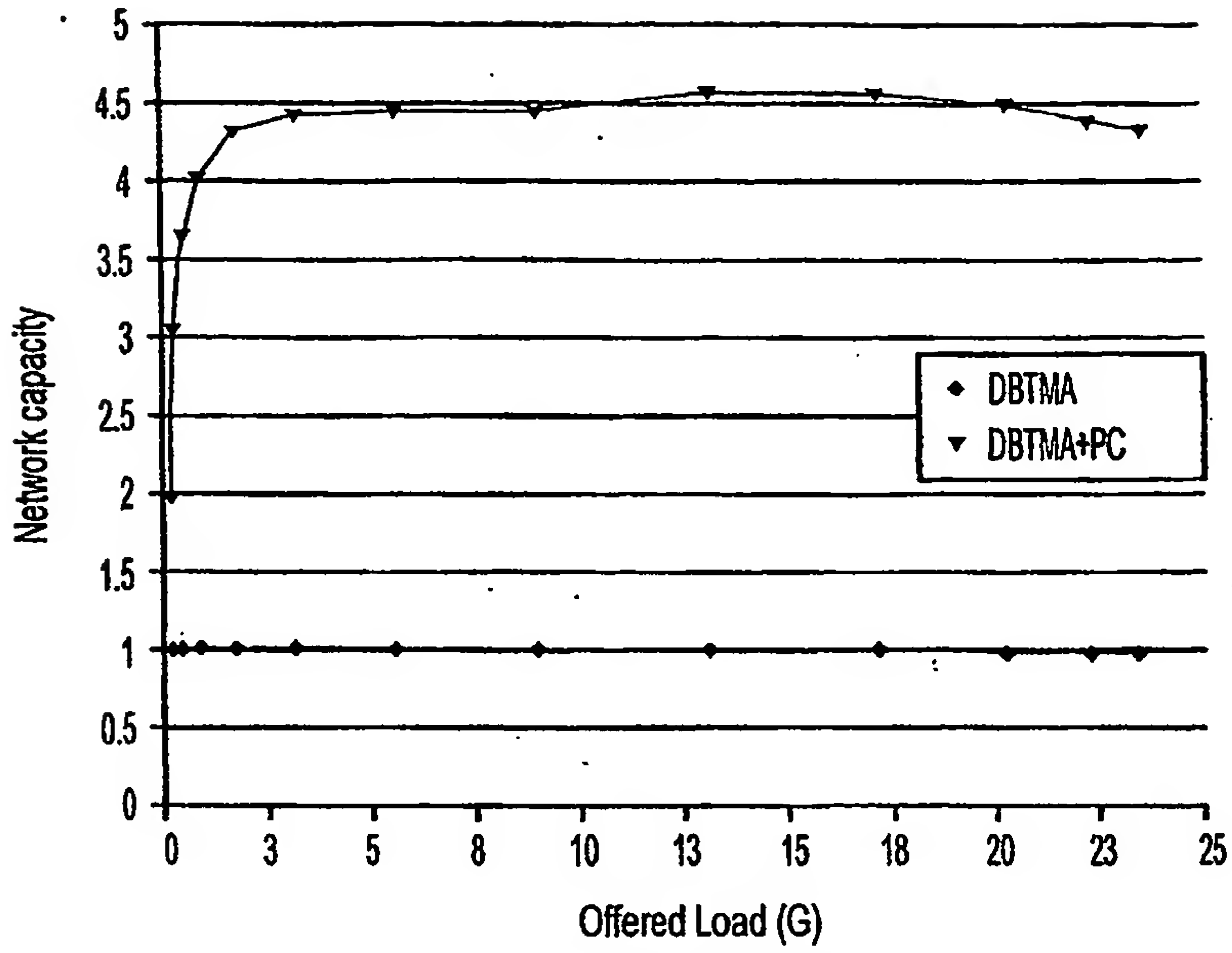

Network capacity
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
3
5
8
10
13
15
18
20
23
25
Offered Load (G)
DBTMA
DBTMA+PC

FIG. 9

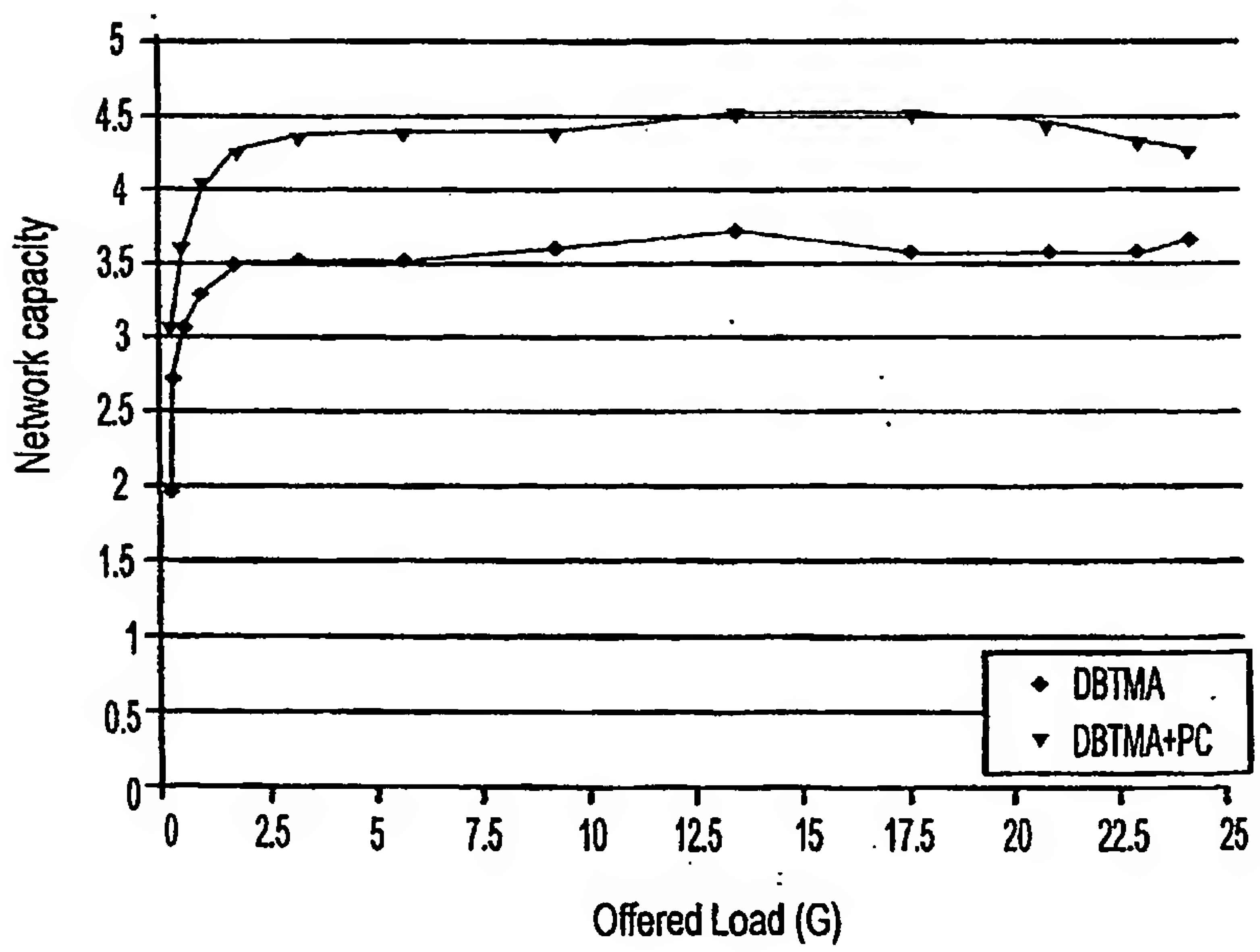

Network capacity
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Offered Load (G)
DBTMA
DBTMA+PC

FIG. 10